IV : EAS phenomenology

EAS:(Extensive Air Shower)

Particle cascade due to the interaction of a cosmic ray in the upper atmosphere.

[Fig 4.1]

Hadronic primaries (nucleon/nucleus) :

At each step the hadronic energy (E_{had}) is shared in 70% E_{had} and 30% E_{EM}. At ground level 90% of the energy (outside the core) is electromagnetic and the remaining 10 % are carried by muons and neutrinos.

[Fig 4.2]

In the EM cascade the low energy particles number is proportional to the total shower energy, i.e. to the primary energy.

$$E_{EM} \propto (N_\gamma + N_{e^+e^-}) < \epsilon > \quad \propto E_{prim}$$

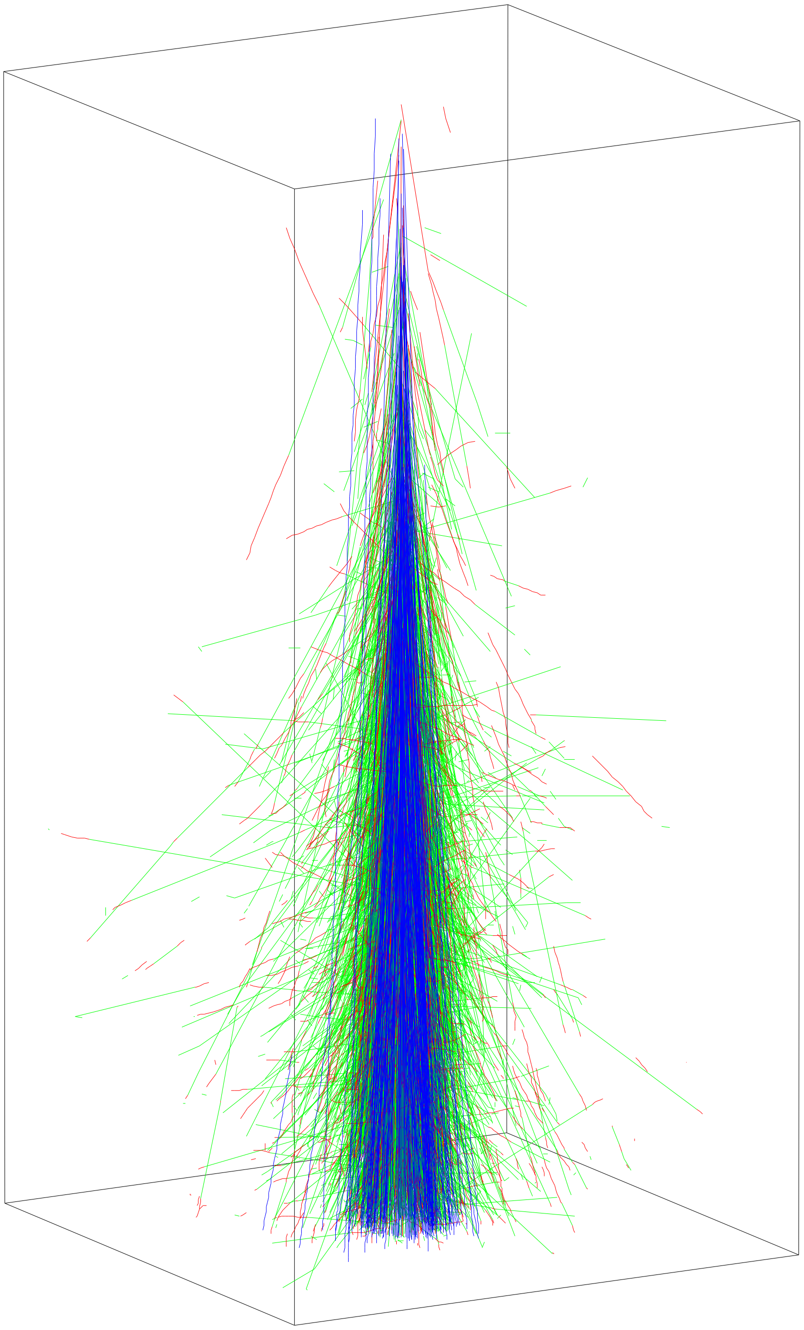
where $< \epsilon >$is the mean photon or electron/positron energy at ground level ($\sim 10 MeV$).

The muon number however does not increase linearly with the primary energy. Muons come from the pion decays whose energy increase faster ($\propto E$) than their number ($\propto log E$).

With a Monte Carlo:

$$N_\mu^p(E) \propto E^{0.85}$$

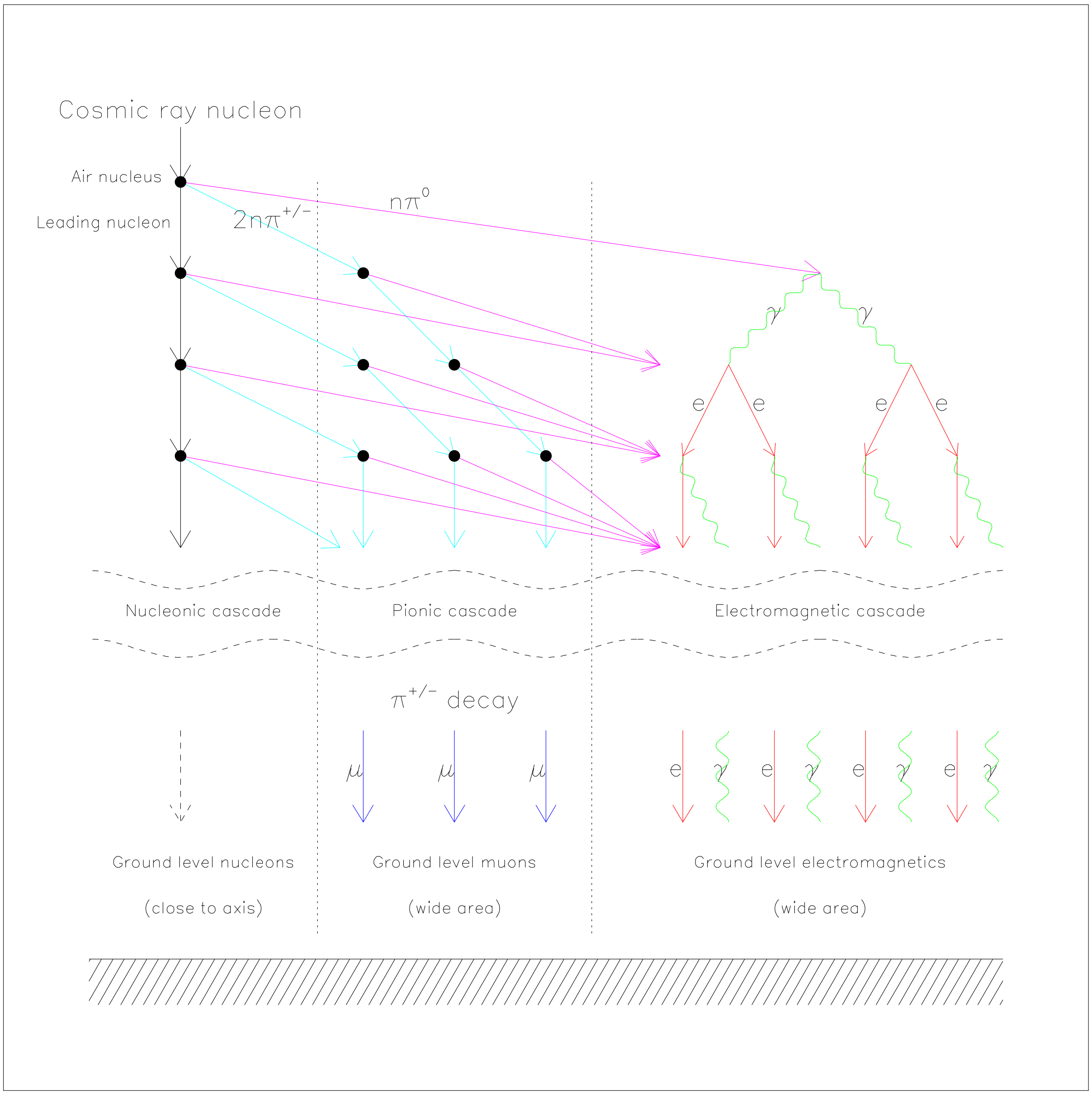
A 10^{19}eV shower



Simulation of a 10^{19}eV proton shower from MOCCA. A sampling of the tracks more than 300m form the core is drawn. The frame is $6 \times 6 \times 12\ km^3$.

Color : green Gamma, red electrons and positrons,blue muons. [Fig 4.1]

Atmospheric developments



Schematic development of an atmospheric shower. Three components are depicted (case of an hadronic primary). Hadronic cascade (leading nucleon) close to the axis (100m), EM cascade (π^0 decay) and pion cascade, the last 2 component extend a few km from the axis.

[Fig 4.2]

Superposition principle : a nucleus ^{A}N is equivalent to A protons thus :

$$N_{\mu}^{A}(E) \propto A^{0.15} \times N_{\mu}^{p}(E)$$

Then a ^{56}Fe primary gives 80% more muons then a proton of the same energy.

"light" primaries

The muons component is small, but more important, the depth of interaction varies from one light particle to the other (proton,photon/neutrino).

The measurements of the muons and EM density ration (ρ_{μ}/ρ_{EM}) gives a lot of information on the primary type.

N.B : Detector response for the same shower varies depending on the detector sensitivity to muons.

Simplified development model

Let λ be the interaction length in Air and E_c the critical energy below which particles only decay or dE/dx. Then :

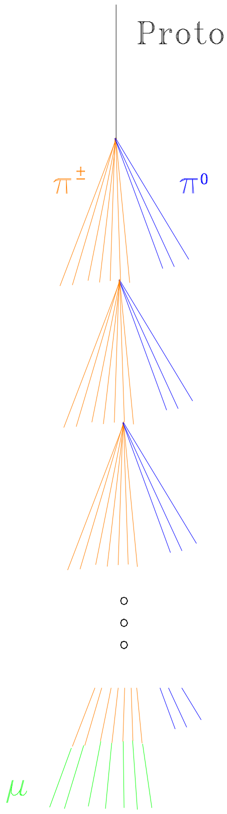
- The particle number at a given depth X grow like $N_s^{X/\lambda}$ (where N_s is the number of secondaries in an interaction).
- The secondaries mean energy is $E(X) = E_0/N(X)$
- As $E_c = E_0/N(X_{max}) = E_0/N_{max}$
- one gets:

$$X_{max} \propto \lambda\, log(E_0) \text{ et } N_{max} \propto E_0$$

where E_0 the primary energy.

[Fig 4.3]

Simplified Model



Energy per pion	$N_{\pi^{\pm}}$
$E_0/10$	$\frac{2}{3}10$
$E_0/100$	$(\frac{2}{3}10)^2$
$E_0/1000$	$(\frac{2}{3}10)^3$
⋮	⋮
$E_c = E_0/10^{n_c}$	$(\frac{2}{3}10)^{n_c}$

$$n_c = \log E_0/E_c$$

$$N_\mu \cong N_{\pi^\pm} = (\tfrac{2}{3}10)^{n_c}$$

$$\log N_\mu = (1+\log \tfrac{2}{3})\ n_c$$

$$= 0.82 \log E_0/E_c$$

$$\boxed{N_\mu \propto E_0^{0.82}}$$

$$\boxed{N_{\mu_A} \propto A\left(\frac{E_0}{A}\right)^{0.82} \quad \text{superposition}}$$

$$\boxed{N_{\mu_A} = A^{1-0.82} N_{\mu_p}} \qquad N_{\mu_{56}} = 1.8\, N_{\mu_p}$$

Heavy nuclei showers have more muons than proton showers with same energy

Heavy nuclei interact higher in the atmosphere than protons with same energy

$$(X_{max})_{Fe} < (X_{max})_p$$

[Fig 4.3]

Spatial structure

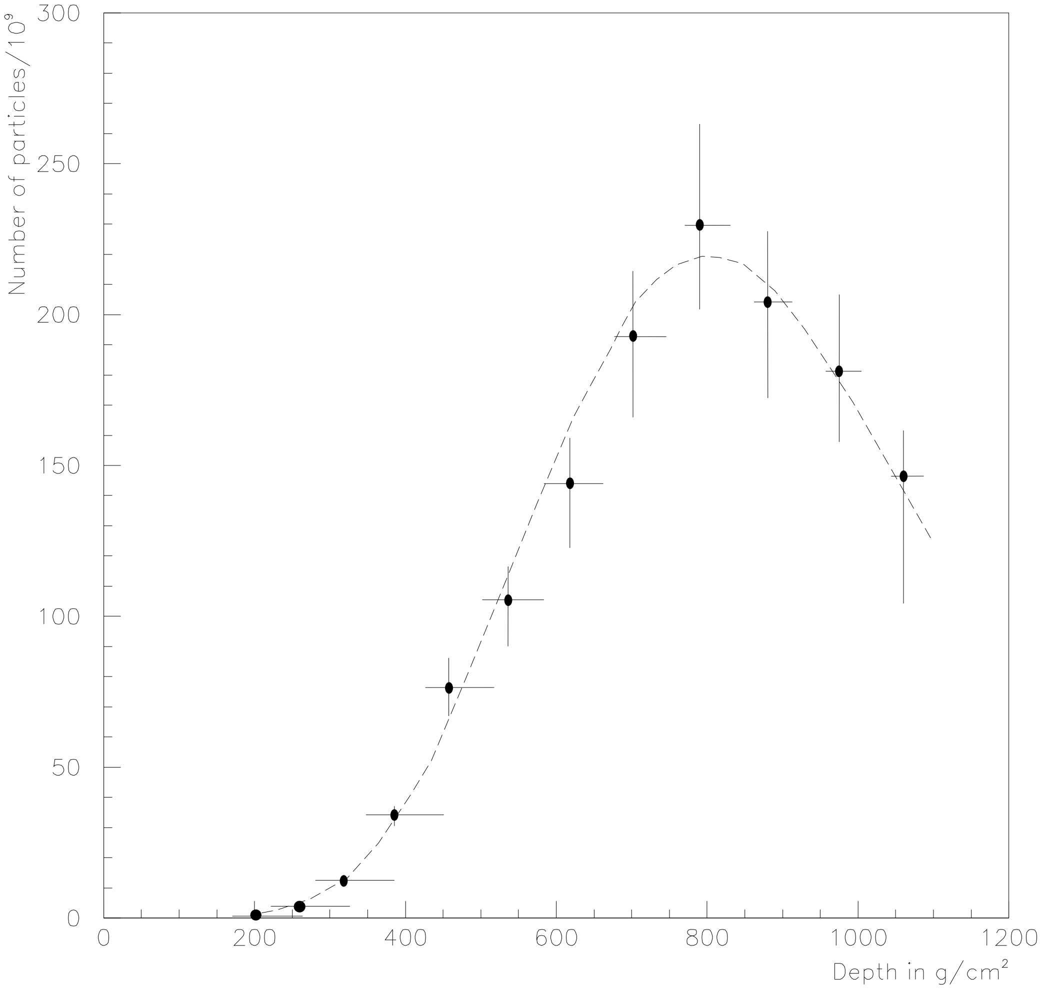
Thin disk (a few μs) of particles moving at the speed of light.

Longitudinal development:

Measured by the Nitrogen fluorescence. N_2 excited by ionizing particle (e^+e^-) emits in the near UV. $\Longrightarrow$ Fluorescence follows the longitudinal development of the shower.

$$N_\gamma^{FD}(X) \propto N_e(X)$$

where X is the thickness (in grams) of atmosphere.



The Fly's Eye event with $3 \times E^{20}\ eV$.

[Fig 4.4]

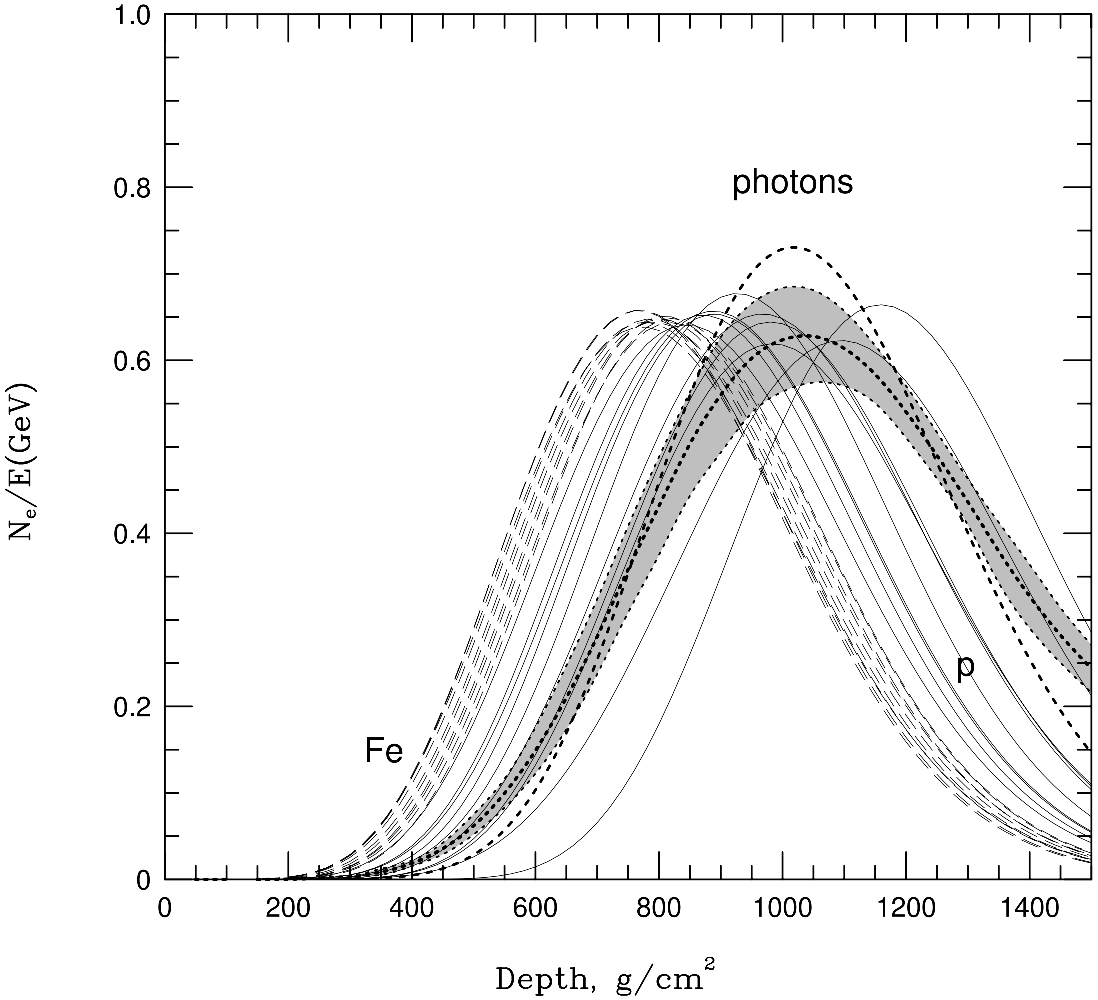
Along the shower the particle number increase and then decrease thus there is a maximum at a certain depth : $X = X_{max}$.

This depth is function of the primary energy and type.

- $X_{max}(10 \times E_0) = X_{max}(E_0) + 55\ (g/cm^2)$

From the superposition model :

- $X_{max}(^{56}F_e; E_0) = X_{max}(p; E_0) - 100\ (g/cm^2)$



[Fig 4.5]

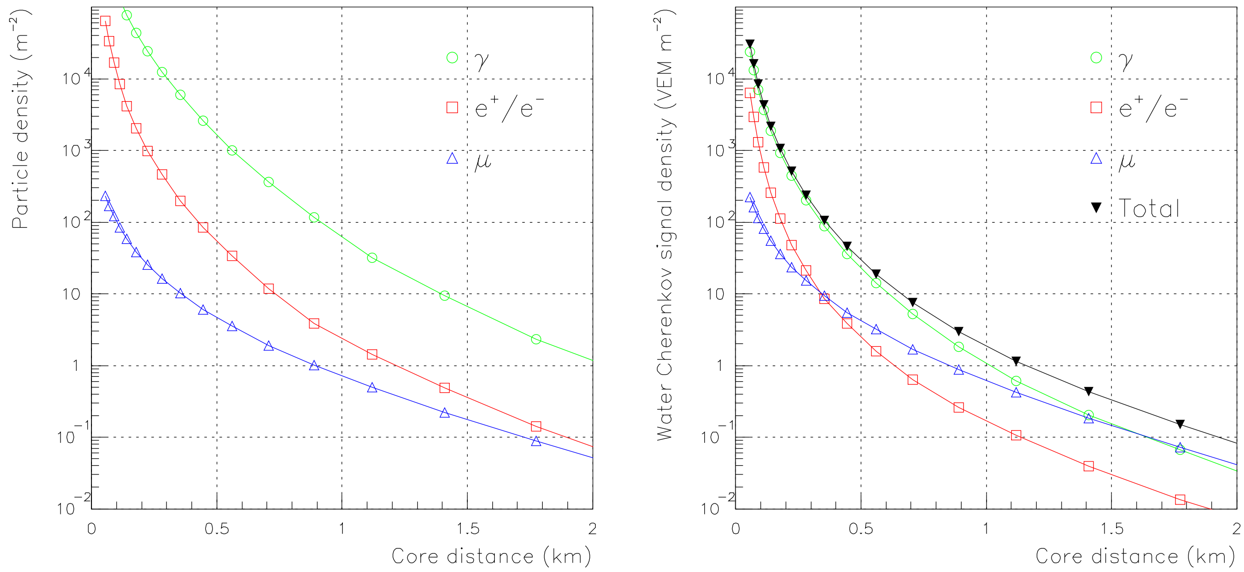
Radial evolution

The radial distribution of showers is driven by the average transverse momentum (P_t) of the interactions and by multiple scattering. In Air the Molière radius is of the order of 80 m.

The particle density as a function of distance to the shower axis is characterized by the "lateral distribution function"

$$\rho(r) \propto k \times r^{-[\eta + f(r)]}$$

where f and k depend on the ground detector type and η upon the primary incident angle and energy. For $r > 800m$ this (empirical) expression must be modified by $(r/800)^{1.03}$.



[Fig 4.6]

Time structure

The shower core is a (moving) source of charged particles and gamma. Those particles can reach detectors far away from the emitting source (the core).

Definition:

Shower plane $\equiv$ Plane tangent to the shower front and perpendicular to the shower axis.

The slight curve of the front of the shower itself can be modeled with a cone. Far from the axis particles arrive after the shower plane (geometry). The particles produced early in the cascade arrive first.

1) Far from the core particles are spread over a time interval : $\Delta T \propto R$. Moreover ΔT increases if X_{max} increases.

2) Muons arrive, in general, earlier than the E.M. component.

1) allows to distinguish small close-by and large far away showers.

2) allows to count muons (at least far from the core)

example:

A $^{56}F_e$ primary gives more muons and interact sooner (higher) in the atmosphere (X_{max} decrease). Consequently the signal rise time (signal proportional to the particle number) will be slower (delayed w.r.t.) than for a proton shower.

Let t_α the time for which $E(t_\alpha) = \alpha \times E(+\infty) \quad \alpha \in [0, 1]$
$E(t)$ is the integrated detector signal amplitude as a function of time.
Then

$$\boxed{t_{\alpha-\beta} = t_\beta - t_\alpha}$$

is an indirect measure of X_{max} i.e. of the primary mass.

Fluctuations

The ground particle distributions depend (only weakly) on the depth and characteristics of the first interactions (strongly dependent on the model used to describe them)

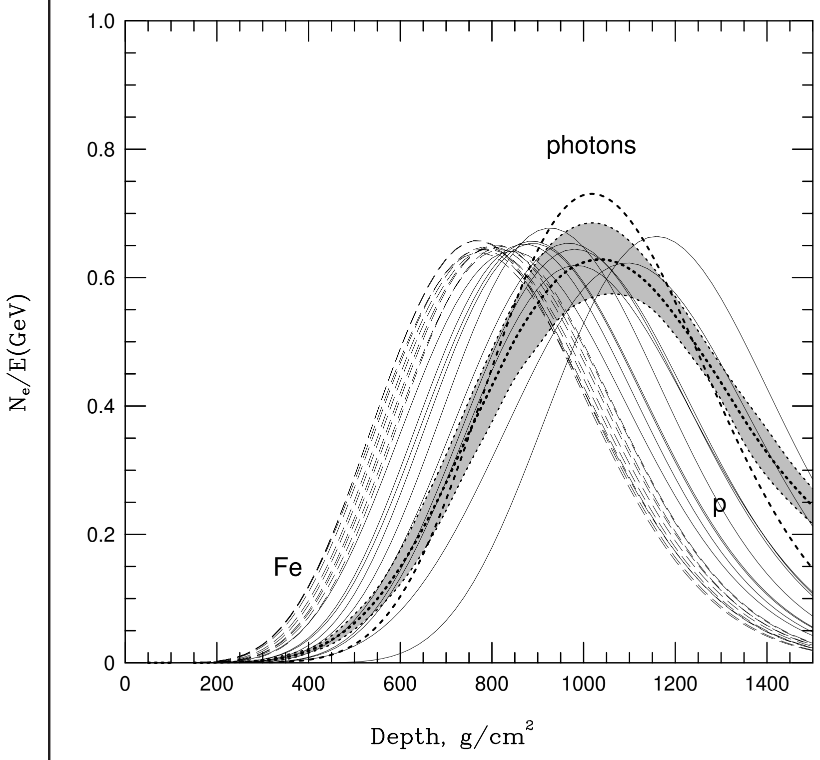
Around 10^{19}eV for protons :

- $\Delta N_\mu \sim 15\%$ and $\Delta N_{em} \sim 5\%$

For Auger those physical fluctuations translate into a signal variation (water Čerenkov) of about 10% at 1 km from the shower core.

Remarks :

There is an optimal distance from the shower core where to estimate the primary energy from the particle density. The shower physical fluctuations (strong near the core) decrease with distance while the particle's density statistical fluctuations increase. The optimal distance, function of the detector spacing and shower mean energy, is about $1\ km$ for Auger.



Protons, Iron and photons showers development curves. 10 shower of each type. For the photons with and without the LPM and the geo-magnetic field effects.